

Review

A Review of the Sustainability Concept and the State of SDG Monitoring Using Remote Sensing

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Received: 4 April 2020; Accepted: 11 May 2020; Published: 31 May 2020



Abstract: The formulation of the 17 sustainable development goals (SDGs) was a major leap forward in humankind's quest for a sustainable future, which likely began in the 17th century, when declining forest resources in Europe led to proposals for the re-establishment and conservation of forests, a strategy that embodies the great idea that the current generation bears responsibility for future generations. Global progress toward SDG fulfillment is monitored by 231 unique social-ecological indicators spread across 169 targets, and remote sensing (RS) provides Earth observation data, directly or indirectly, for 30 (18%) of these indicators. Unfortunately, the UN Global Sustainable Development Report 2019—The Future is Now: Science for Achieving Sustainable Development concluded that, despite initial efforts, the world is not yet on track for achieving most of the SDG targets. Meanwhile, through the EO4SDG initiative by the Group on Earth Observations, the full potential of RS for SDG monitoring is now being explored at a global scale. As of April 2020, preliminary statistical data were available for 21 (70%) of the 30 RS-based SDG indicators, according to the Global SDG Indicators Database. Ten (33%) of the RS-based SDG indicators have also been included in the SDG Index and Dashboards found in the Sustainable Development Report 2019—Transformations to Achieve the Sustainable Development Goals. These statistics, however, do not necessarily reflect the actual status and availability of raw and processed geospatial data for the RS-based indicators, which remains an important issue. Nevertheless, various initiatives have been started to address the need for open access data. RS data can also help in the development of other potentially relevant complementary indicators or sub-indicators. By doing so, they can help meet one of the current challenges of SDG monitoring, which is how best to operationalize the SDG indicators.

Keywords: sustainable development; Earth observation; SDG indicators; EO4SDG; SDG global indicator framework; global SDG indicators database; social-ecological indicators

1. Introduction

In the report “Our Common Future” (also known as the Brundtland Report), the World Commission on Environment and Development has defined sustainable development as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” [1]. This principle is at the core of the 17 sustainable development goals (SDGs) adopted in 2015 by the United Nations (UN) General Assembly [2]. These SDGs collectively help to guide actions for global development and shape visions for the future. At the global level, the UN Statistical Commission serves as the oversight body for SDG efforts. The commission oversees the UN Statistics Division, which is responsible for the maintenance of the Global SDG Indicators Database.

In 2015, the UN Statistical Commission created the Inter-agency and Expert Group on SDGs (IAEG-SDGs), which was tasked with the development and implementation of a global indicator framework for monitoring global progress toward fulfillment of the 17 SDGs. In 2017, the UN General Assembly adopted the global indicator framework developed by the IAEG-SDGs. In the adopted

framework, various social-ecological indicators are identified and assigned to the SDG targets [3,4]. Here, the term “social” includes both the social and economic dimensions of sustainability, whereas the term “ecological” refers to its environmental dimension. Together, these are often referred to as the three pillars of sustainability: people (social), profit (economic), and planet (environmental), respectively [5–7]. In this review, the social-ecological indicators are regarded as a set of outcomes for assessing and monitoring the sustainability of social-ecological systems (also called human–environment systems, coupled human–environment systems, and coupled human and natural systems [8,9]), analyzed in the context of the social-ecological system framework proposed by Elinor Ostrom [10–12].

Among various descriptions of indicators [13–15], one that is often cited states that “desirable indicators are those that summarize or otherwise simplify relevant information, makes [sic] visible or perceptible phenomena of interest, and quantify, measure, and communicate relevant information” [13] (p. 108). Indicators, like goals [16], should also be SMART: specific, measurable, achievable, relevant, and time-bound [17]. The major functions of indicators are to (i) assess conditions and trends, (ii) compare across places and situations, (iii) assess conditions and trends in relation to goals and targets, (iv) provide early warning information, and (v) anticipate future conditions and trends [13]. The SDG global indicator framework, though developed primarily for monitoring global progress toward achievement of the SDGs [2,4], supports all these indicator functions. More generally, sustainable development indicators are “scientific constructs whose principal objective is to inform public policy-making” [18] (p. 45).

The achievement of SDGs relies on the performance of countries with respect to the SDG targets and indicators. Thus, the development of methodologies for monitoring progress toward SDG achievement has become “a new vital science” [19]. Custodian agencies are responsible for the development of the necessary methodologies and the collection and compilation of data related to SDG indicators. The international organizations and agencies designated as custodian agencies by the IAEG-SDGs include the World Health Organization (WHO), the Food and Agriculture Organization (FAO), the United Nations Development Programme (UNDP), and the World Bank [20]. Available data for all SDG indicators are compiled in the Global SDG Indicators Database (<https://unstats.un.org/sdgs/indicators/database>), and the UN Statistics Division also issues annual SDG progress reports (<https://unstats.un.org/sdgs/>).

The global indicator framework includes a total of 231 unique indicators spread across 169 SDG targets [3,21]. Twelve indicators are associated with two or three targets [3,21]. SDG 17 (Partnerships for the Goals) has the highest number of targets, with 19, followed by SDG 3 (Good Health and Well-Being) with 13 (Figure 1). By contrast, SDGs 7 (Affordable and Clean Energy) and 13 (Climate Action) have the lowest number of targets, with five each. SDG 3 has the largest number of indicators (28), followed by SDGs 16 (Peace, Justice and Strong Institutions) and 17 (24 each), and SDGs 7 and 13 have the smallest number of indicators (6 and 8, respectively).

The SDG indicators are classified into three tiers according to the level of methodological development and the global availability of data as follows [20]: a Tier I indicator “is conceptually clear, has an internationally established methodology and standards are available, and data are regularly produced by countries for at least 50 per cent of countries and of the population in every region where the indicator is relevant.” A Tier II indicator “is conceptually clear, has an internationally established methodology and standards are available, but data are not regularly produced by countries.” For a Tier III indicator, “no internationally established methodology or standards are yet available for the indicator, but methodology/standards are being (or will be) developed or tested.” Indicators for which data availability is under review are labeled as “pending data availability review” [20].

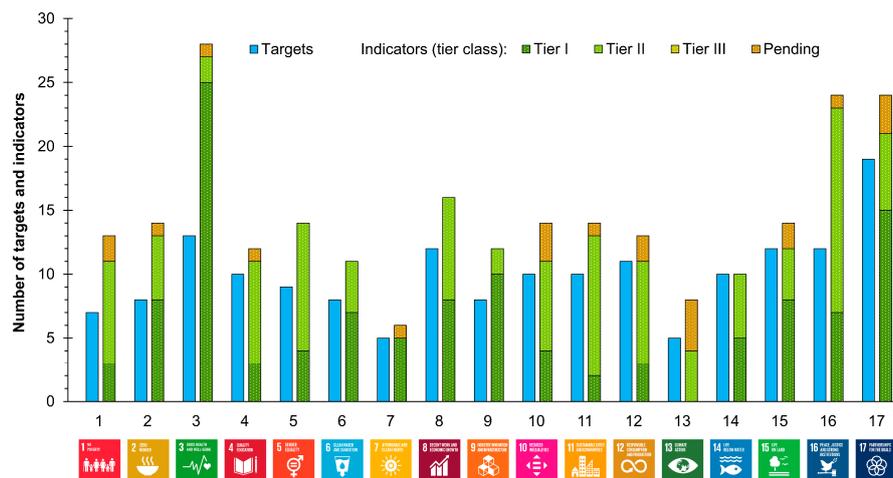


Figure 1. Distribution of targets and indicators across the 17 SDGs. These data were sourced from the March 2020 version of the global indicator framework for the SDGs [3] and the April 2020 version of the tier classification for global SDG indicators [20]. The global indicator framework was adopted by the UN General Assembly in July 2017 and is contained in the resolution designated A/RES/71/313 [4,21]. As of this writing, the latest version of the list of SDG indicators bears the following notations in the upper right corner of the downloadable PDF document: A/RES/71/313, E/CN.3/2018/2, E/CN.3/2019/2, and E/CN.3/2020/2 [3]. These notations mean that the current official list of indicators [3] includes the global indicator framework as contained in A/RES/71/313, the refinements agreed by the UN Statistical Commission at its 49th session in March 2018 (E/CN.3/2018/2, Annex II) and 50th session in March 2019 (E/CN.3/2019/2, Annex II), and the changes from the 2020 Comprehensive Review (E/CN.3/2020/2, Annex II) and annual refinements (E/CN.3/2020/2, Annex III) from the 51st session in March 2020 [21].

Explicit in the 2030 Agenda (Transforming Our World: The 2030 Agenda for Sustainable Development) is a declaration (no. 76) to support developing countries by ensuring access to high-quality, timely, reliable, and disaggregated data, including geospatial and Earth observation data [2]. Recognizing that the “integration of statistical data and geospatial information will be key for the production of a number of indicators,” the IAEG-SDGs created the Working Group on Geospatial Information (WGGI) in 2016 [22] (p. 1) under the UN’s Committee of Experts on Global Geospatial Information Management (UN-GGIM). The primary objective of the WGGI is “to ensure from a statistical and geospatial perspective that one of the key principles of the 2030 Agenda, to leave no one behind, is reflected in the global indicator framework” [22] (p. 2).

The Group on Earth Observations (GEO), created in 2005, is a global partnership of governments and organizations that “envisions a future where decisions and actions for the benefit of humankind are informed by coordinated, comprehensive and sustained Earth observations” (www.earthobservations.org). In 2016, recognizing the potential of Earth observation data for SDG monitoring, the GEO launched an initiative called “Earth Observations in Service of the 2030 Agenda for Sustainable Development” (EO4SDG) (<http://eo4sdg.org/>) [23–25]. The purpose of this initiative is to “organize and realize the potential of Earth observations and geospatial information to advance the 2030 Agenda and enable societal benefits through achievement of the Sustainable Development Goals” [25] (p. 4). The EO4SDG initiative set forth three goals in its Strategic Implementation Plan 2020–2024: “(i) demonstrate how Earth observations, geospatial information, and socio-economic and other data contribute in novel and practical ways to support sustainable development efforts and the SDGs, (ii) increase skills and capabilities in uses of Earth observations for SDG activities and their broader benefits, and (iii) broaden interest, awareness, and understanding of Earth observations support to the SDGs and contributions to social, environmental, and economic benefits” [25] (p. 4).

A couple of years into the implementation of the 2030 Agenda, the GEO has seen an increasing demand for EO data for monitoring progress toward achievement of the SDGs [25]. The GEO has

identified 71 (42%) targets and 30 (13%) indicators for the SDGs that can be supported, directly or indirectly, by EO data [25] (see Section 4). The EO4SDG initiative supports the WGGI task stream called "Application of Earth Observations for the SDG Indicators" [25].

The purpose of this review is to describe the conceptualization of sustainability leading to the formulation of the SDGs and then to discuss the current status, challenges, and opportunities in SDG monitoring using remote sensing (RS).

2. Review Approach

This review is intended to be an overview, that is, a survey of the literature and a description of its characteristics [26]. The search and appraisal of reference materials for this review did not follow a set of pre-defined rules as would be done for a systematic review. Potentially relevant reference materials were searched online and appraised according to whether they included information on the conceptualization of sustainability and SDG monitoring with RS. This review thus aims to provide a broad introductory understanding of (a) the conceptualization of sustainability leading to the formulation of the SDGs, (b) the role of RS in SDG monitoring, and (c) the current status, challenges, and opportunities of SDG monitoring with RS.

3. From the Conceptualization of Sustainability to the Formulation of the SDGs

This section provides an overview of the historical origin and development of the sustainability concept and the progression that eventually led to the formulation of the SDGs. In the past three decades, a number of works have addressed this topic. Kidd [27], who focused on the development of the sustainability concept in the 19th and 20th centuries, suggested that the concept has its origins in six ideas (termed "roots"): the ecological/carrying capacity root, the resource/environment root, the biosphere root, the critique of technology root, the no growth-slow growth root, and the ecodevelopment root. According to Grober [28], the sustainability concept probably originated in the 17th and 18th centuries when declining forests in Europe led to the idea that sustained yield (or sustainable use) of forest resources could be achieved through conservation and reforestation. Warde [29], however, thought that the "invention of sustainability" might have occurred earlier, between c. 1500 and 1870.

A timeline of the conceptual development of sustainability (Figure 2) shows that before 1970, the literature on sustainability was dominated by books and essays, whereas after 1970, peer-reviewed articles and global policy initiatives and reports became more dominant. Indeed, environmental issues and initiatives reached the global stage when the UN General Assembly convened in the 1972 Stockholm Conference. Before this conference, environmental governance was apparently not considered to be an international priority. The Stockholm Conference led to the Declaration on the Human Environment (Stockholm Declaration) and resulted in the creation of the UN Environment Programme (UNEP), which is today "the global champion for the environment with programmes focusing on sustainable development, climate, biodiversity and more" (www.unenvironment.org).

Historically, the sustainability concept has its roots in the works of English author John Evelyn (*Sylva*, 1664) and the French statesman Jean Baptist Colbert (*Ordonnance*, 1669), who called for the re-establishment and conservation of forests [28,30] (Figure 2). Although the focus of these works was on Europe, both books included the idea that the current generation has responsibility for future generations [28]. Moreover, they were important sources and models for German nobleman Hanns Carl von Carlowitz [28]. In 1713, von Carlowitz published *Sylvicultura Oeconomica*, in which he introduced the term "sustainable" in its modern sense for the first time: in German, "*nachhaltende Nutzung*," referring to the "sustainable use" [31] or "sustained use" [28] of forest resources. During the 18th century, *nachhaltend* was modified to *nachhaltig*, and the use of the related noun *nachhaltigkeit*, with reference to "sustained yield" forestry, became widespread [28]. Today, *nachhaltigkeit* is generally translated as "sustainability."

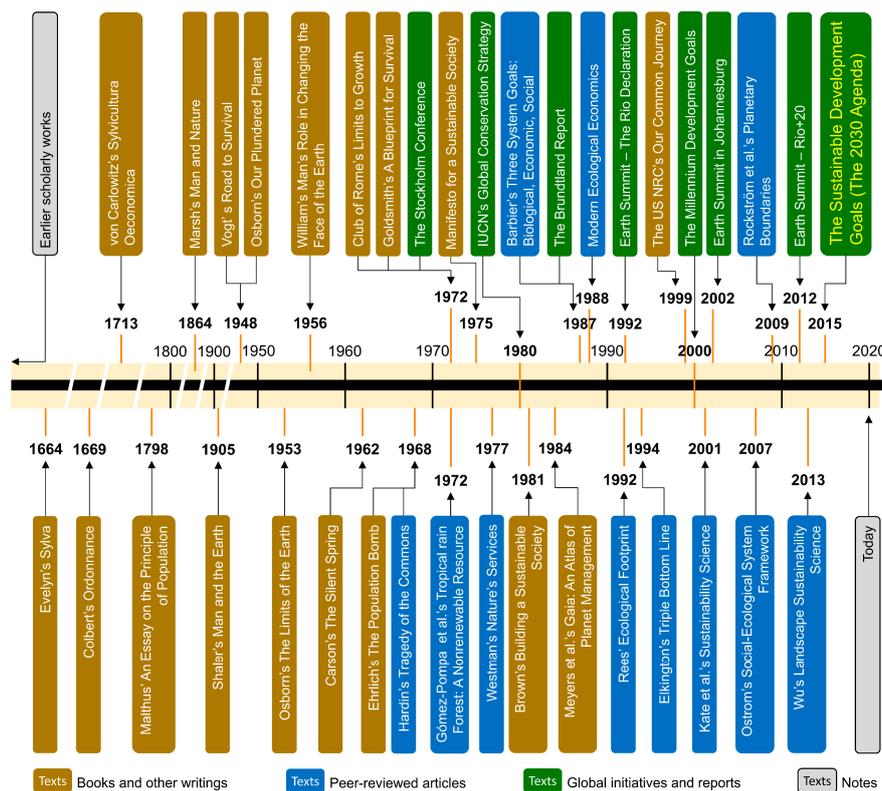


Figure 2. Timeline showing how the sustainability concept has been advanced by scholarly works and global policy initiatives.

Over the past three centuries, many influential books have contributed to the development of the sustainability concept as we understand it today (Figure 2). These include *An Essay on the Principle of Population* (1798) by Thomas Robert Malthus, *Man and Nature* (1864) by George Perkins Marsh, *Man and the Earth* (1905) by Nathaniel Shaler, *Road to Survival* (1948) by William Vogt, *Our Plundered Planet* (1948) and *The Limits of the Earth* (1953) by Fairfield Osborn, *Man's Role in Changing the Face of the Earth* (1956) by William L. Thomas, Jr., *The Silent Spring* (1962) by Rachel Carson, *The Population Bomb* (1968) by Paul R. Ehrlich and Anne H. Ehrlich, *Limits to Growth* (1972) by the Club of Rome, and *A Blueprint for Survival* (1972) by Edward Goldsmith and Robert Allen. Reviews of the sustainability concept and its origin, including the conceptualization of sustainable development, commonly cite these books [27,30,31]. However, the term "sustainable development," as presented in the Brundtland Report (1987) [1], was first used in *World Conservation Strategy*, published in 1980 by the International Union for Conservation of Nature (IUCN) [32]. Other works contributing to the conceptualization of sustainable development include *Building a Sustainable Society* (1981) by Lester R. Brown and *Gaia: An Atlas of Planet Management* (1984) by Norman Meyers and colleagues [31].

Among articles in peer-reviewed journals that have helped shape and advance the sustainability concept, "The tragedy of the commons" (1968) [33] was one of the earliest and most influential. The "tragedy of the commons" is that, in the absence of proper regulation, self-interest can lead to the over-exploitation and destruction of non-renewable common resources, such as the atmosphere, the ocean, and biodiversity, threatening their sustainability. "Tropical rain forest: A nonrenewable resource" (1972) [34] emphasized the importance of tropical rainforests as a non-renewable resource. "How much are nature's services worth?" [35] introduced the concept of nature's services, which, together with some other works [36,37], led to the "ecosystem services" concept [38]. Interestingly, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) recently proposed, without referring to these earlier works, "nature's contribution to people" as an umbrella term that also includes ecosystem services [39,40]. The ecosystem services concept gained popularity with the publication of

the book *Nature's Services: Societal Dependence on Natural Ecosystems* (1997) [41], the article "The value of the world's ecosystem services and natural capital", which appeared in *Nature* in 1997 [42], and the Millennium Ecosystem Assessment report in 2005 (www.millenniumassessment.org/).

Several important ideas have helped advance the sustainability concept. In 1987, Barbier [5] introduced the three system goals of sustainability (biological and resource, economic, and social), which might be the origin of the idea that there are three pillars, dimensions, components, or aspects of sustainability [30,43]. Along with Barbier's work [5], the notion of the triple bottom line [6,7] also contributed to the idea that there are three pillars of sustainability. Ecological economics, a transdisciplinary field of study [44,45], has helped advance the concept of natural capital, a term first used by Ernst F. Schumacher in his book *Small is Beautiful* (1973). The ecological footprint concept [46] eventually led to the establishment of the global footprint network, which aims to advance the science of sustainability. The term "sustainability science" [47] was introduced in *Our Common Journey: A Transition Toward Sustainability* (1999) by the US National Research Council (NRC) [48]. The field of sustainability science has since been advanced by the development of the social-ecological system framework [10] which couples human and environmental systems. In this context, the planetary boundaries concept [49] aims to define a safe operating space for humanity, and landscape sustainability science [50] focuses on the dynamic relationship between ecosystem services and human well-being.

The development of the idea of the human-environment system, together with global initiatives such as the Earth Summit and the Millennium Development Goals (MDGs) (see Figure 2), have helped advance the field of sustainability science and influenced the formulation of the current SDGs. In particular, the three pillars of sustainability are explicitly embedded in the formulation of the SDGs [30,51]. However, the sustainability (or sustainable development) concept is frequently criticized as vague and ambiguous [52–56]. These critiques ask, the sustainability of what and for whom? This reviewer argues that, in the context of the SDGs, sustainability means the sustainability of Earth's resources—its life-support system—for the benefit, or at least for the survival, of the current and future generations of humankind.

In their comprehensive review on the conceptual evolution of sustainability, Purvis et al. [30] suggest that the concepts of the three pillars of sustainability (social, economic, and environmental) do not have theoretically rigorous support, and they conclude that "the absence of such a theoretically solid conception frustrates approaches towards a theoretically rigorous operationalisation of 'sustainability'" [30] (p. 681). This reviewer recognizes this issue. Nevertheless, the viewpoint of this reviewer is that the idea of sustainability is of great importance to humanity, because, like the concepts of freedom, justice, and democracy, which are also dialectically vague, it expresses a fundamental principle that can guide our actions and shape our visions for the future [50,57].

4. The Role of Remote Sensing for SDG Monitoring

The development of a "human capability to observe regions of the electromagnetic spectrum outside the range of wavelengths discernable by the human eye" was fundamental to the evolution of remote sensing technology [58] (p. 685). The term "remote sensing" was coined in the 1950s by Evelyn Pruitt, a geographer and oceanographer formerly with the Office of Naval Research (<https://earthobservatory.nasa.gov/features/RemoteSensing>). According to Gerald K. Moore [59] (p. 478), remote sensing is "the use of reflected and emitted energy to measure the physical properties of distant objects and their surroundings". The Encyclopedia of Remote Sensing defines remote sensing as "the technique of obtaining information about objects through the analysis of data collected by special instruments that are not in physical contact with the objects of investigation" [58] (p. 684). Nicholas M. Short, in his Remote Sensing Tutorial (An Online Handbook), has defined remote sensing as "the acquisition and measurement of data/information on some property(ies) of a phenomenon, object, or material by a recording device not in physical, intimate contact with the feature(s) under surveillance; techniques involve amassing knowledge pertinent to environments by measuring force fields, electromagnetic radiation, or acoustic energy employing cameras, radiometers and scanners,

lasers, radio frequency receivers, radar systems, sonar, thermal devices, seismographs, magnetometers, gravimeters, scintillometers, and other instruments.”

Remote sensing (RS) is multi-functional because it is (1) a source of basic data, (2) a science, and (3) a tool. RS is a source of basic data because the measurements of physical properties of distant objects and their surroundings with the use of reflected and emitted energy are themselves data, regardless of where they are recorded [59]. RS is a science because it utilizes a scientific process: measurements, data processing, interpretation of the results, and scientific inference [59]. Finally, RS is a tool because results obtained from this scientific process can be used for various purposes, from the making of inventories of resources to the solving of ecological problems [59].

Monitoring of the SDG indicators is vital, and Earth observation technologies such as RS have an important role to play in indicator monitoring. RS data are particularly useful because they can be used for both temporal and spatial monitoring. As early as two decades ago, before the formulation of the SDGs [2,51] and launch of the EO4SDG initiative [23–25], and also before the development of concepts such as “seeing sustainability from space” [60] and “remote sensing for sustainability” [61], Rao [62] foresaw the potential of RS technology for sustainability-related research and for helping to achieve sustainable development. Through the EO4SDG initiative, the potential of RS technology is now being explored at a global scale. RS-derived data have been shown to be useful across many fields, such as in the field of land cover monitoring and ecosystem assessment [63–71], hydrological studies [72,73], meteorological/climatological and climate change studies [74,75], thermal and urban remote sensing [76–85], air quality monitoring [86,87], health geographics [88–91], and disaster risk management [92,93].

The importance of EO technologies such as RS has become more apparent with the formulation of the SDG framework, compared with their importance to its predecessor, the Millennium Development Goals (MDG) framework (www.un.org/millenniumgoals/). Although the MDG framework helped narrow the data gap with regard to the social dimension of sustainability, the inclusion of various environmental indicators under the SDG targets has increased the need for accurate, timely, and reliable environmental data. RS is an important environmental monitoring tool that can help fill gaps in environmental data [24,25,94].

Some essential characteristics of RS data have important advantages for SDG monitoring: spatial resolutions ranging from coarse to very high; temporal resolutions ranging from ca. bimonthly to daily; various spectral resolutions; spatial scales from local to global; long-period time series (starting from 1972 for Landsat); consistency (in terms of data capture or measurement); and complementarity (ability to be validated) [95] (Tables A1 and A2). These features mean that RS data are useful for the development of policy-relevant environmental SDG indicators [94,95] that can be monitored over space and time.

The 30 social-ecological indicators that can be directly or indirectly supported by EO data [25] are related to 13 SDGs (Figures 3 and A1). Among these 13 SDGs, SDGs 6 (Clean Water and Sanitation), 11 (Sustainable Cities and Communities), 14 (Life Below Water), and 15 (Life on Land) offer “the greatest opportunities for the application of EO data” [25] (p. 8). Information on the current status of these RS-based indicators is given in Section 5 and Figure 3.

In general, the monitoring of progress toward achieving the SDGs by way of the SDG global indicator framework increases the demand for various statistical data from countries all over the world. This increased demand for these data necessitates an increase in investments of money, manpower, and time in building the capacity of national statistical offices—investments that might be better made in research and substantive development projects with clear impacts on meeting SDG targets [96]. In this regard, the EO4SDG initiative is especially important for developing regions that have low capacity for database development. Moreover, the potential use of EO data for more indicators, in addition to the 30 indicated currently identified as EO-supported, presents valuable opportunities in research and development (details are discussed in Section 5).

	Goal	Indicators				
	No Poverty	1.4.2 Tier II				
	Zero Hunger	2.4.1 Tier II				
	Good Health and Well-Being	3.9.1 Tier I				
	Quality Education					
	Gender Equality	5.a.1 Tier II				
	Clean Water and Sanitation	6.3.1 Tier II	6.3.2 Tier II	6.4.2 Tier I	6.5.1 Tier I	6.6.1 Tier I
	Affordable and Clean Energy	7.1.1 Tier I				
	Decent Work and Economic Growth					
	Industry, Innovation and Infrastructure	9.1.1 Tier II	9.4.1 Tier I			
	Reduced Inequalities					
	Sustainable Cities and Communities	11.1.1 Tier I	11.2.1 Tier II	11.3.1 Tier II	11.6.2 Tier I	11.7.1 Tier II
	Responsible Consumption and Production	12.a.1 Tier Pending				
	Climate Action	13.1.1 Tier II				
	Life Below Water	14.1.1 Tier II	14.3.1 Tier II	14.4.1 Tier I	14.5.1 Tier I	
	Life on Land	15.1.1 Tier I	15.2.1 Tier I	15.3.1 Tier I	15.4.1 Tier I	15.4.2 Tier I
	Peace, Justice and Strong Institutions					
	Partnerships for the Goals	17.6.1 Tier I	17.18.1 Tier Pending			

Data availability (as of April 2020)
 Available
 Not available

Inclusion in the 2019 SDG Index and Dashboards
● Included (exact indicator)
● Included (proxy indicator)
● Not included

Figure 3. Current status of the RS-based SDG indicators. This list of indicators is based on GEO [25]. Data availability is based on the Global SDG Indicators Database as of April 2020 (<https://unstats.un.org/sdgs/indicators/database/>). The 2019 SDG Index and Dashboards are available in the Sustainable Development Report 2019 [97]. The tier classification of the indicators are those as of April 2020 [20].

5. Current Status, Challenges, and Opportunities

5.1. Status of the 2030 Agenda

Just under 10 years remain to achieve the 2030 Agenda. The UN Global Sustainable Development Report 2019 (UN-GSDR 2019) [98] has concluded that (i) despite initial efforts, the world is not on track for achieving most of the 169 targets that comprise the SDGs, (ii) recent trends along several dimensions with cross-cutting impacts across the entire 2030 Agenda (rising inequalities, climate change, biodiversity loss, and increasing amounts of waste from human activity) are not even moving in the right direction, (iii) under current trends, the world's social and natural biophysical systems

cannot support the aspirations for universal human well-being embedded in the SDGs, and (iv) no country is yet convincingly able to meet a set of basic human needs at a globally sustainable level of resource use.

To achieve the desired transformations at the necessary scale and speed, the UN-GSDR 2019 identifies six entry points: human well-being and capabilities, sustainable and just outcomes, food systems and nutrition patterns, energy decarbonization with universal access, urban and peri-urban development, and global environmental commons [98]. It also identifies four levers that “can be coherently deployed through each entry point to bring about the necessary transformations”: governance, economy and finance, individual and collective action, and science and technology [98] (p. xxi).

The report also highlights the importance of sustainability science [47] to “help tackle the trade-offs and contested issues involved in implementing the 2030 Agenda.” Accordingly, “new initiatives are needed that bring together science communities, policymakers, funders, representatives of lay, practical and indigenous knowledge and other stakeholders to scale up sustainability science and transform scientific institutions towards engaged knowledge production for sustainable development.” To achieve this, the UN “should launch a globally coordinated knowledge platform to synthesize existing international and country-by-country expertise on transformation pathways from scientific and nonscientific sources, including lay, practical and indigenous knowledge,” and, at the same time, “educational institutions at every level, especially universities, should incorporate high-quality theoretical and practically oriented courses of study on sustainable development” [98] (p. 120).

One feedback on the UN-GSDR 2019 relates to the effort paid to the improvement of the SDG global indicator framework, because although there are frequent opportunities for input, clarity and transparency on the dynamics of decision-making is less frequent [96]. The fear is that more is being invested in the development of the SDG global indicator framework, including its databases, than is being invested in actual projects that can deliver desirable outcomes and bring about progress, and, as a result, “many of the targets will not only not be met, but unless things change radically, will never be met” [96] (p. 5).

The standpoint of this reviewer is that, although both the refinement of the SDG global indicator framework and the development of relevant databases are necessary to enable the monitoring of progress toward the SDGs, these activities should not overshadow the need to implement projects needed to help achieve the SDGs and which can be expected to have actual and positive impacts on people’s lives, society, and the environment.

5.2. Status of the RS-Based Indicators and Their Inclusion in the SDG Index 2019

As of April 2020, 21 (70%) of the 30 RS-based SDG indicators have at least some preliminary statistical data, according to the Global SDG Indicators Database (Figure 3; Table 1). Among those indicators with statistical data, 16 are classified as Tier 1 and five as Tier II indicators. Among the nine indicators still without statistical data, seven are Tier II indicators and the tier classification of the other two is pending. None of the 30 RS-based indicators is currently classified as a Tier III indicator [20].

The SDG indicators are also being monitored indirectly by the UN Sustainable Development Solutions Network (SDSN), in partnership with the Bertelsmann Stiftung (BS), which produces annual reports that assess each country’s performance on the 17 SDGs [97]. The mission of the SDSN, which was set up in 2012 at the direction of the UN Secretary-General, is to “mobilize global scientific and technological expertise to promote practical solutions for sustainable development, including the implementation of the SDGs and the Paris Climate Agreement” (www.unsdsn.org). The SDG Index and Dashboards (SDR-ID 2019) includes 10 (33%) of the RS-based indicators (Figure 3) [97]; six of these exactly match official SDG indicators, and the other four are proxy indicators that are related to or closely aligned with official indicators.

Table 1. Status of remote sensing (RS)-based sustainable development goals (SDG) indicators. Only those indicators with data as of April 2020, according to the Global SDG Indicators Database (<https://unstats.un.org/sdgs/indicators/database/>), are included. The complete list of RS-based SDG indicators is given in Figure 3. The custodian and tier classification information is current as of April 2020 [20]. The number of countries/territories/regions is for the described variable only.

RS-based SDG Indicator	Custodian	Tier	Available Data		
			No. and Name of Data Variables	Year	No. of Countries/Territories/Regions
3.9.1 Mortality rate attributed to household and ambient air pollution	WHO	I	6 The 6th variable is the crude death rate attributed to household and ambient air pollution	2016	219
5.a.1 (a) Proportion of total agricultural population with ownership or secure rights over agricultural land, by sex; and (b) share of women among owners or rights-bearers of agricultural land, by type of tenure	FAO	II	2 The 1st variable is proportion of people with ownership or secure rights over agricultural land, by sex	2009–2019 (varies by country/territory)	10 (total for all data years)
6.3.1 Proportion of wastewater safely treated	WHO, UN-Habitat, UNSD	II	1 Proportion of safely treated domestic wastewater flows	2018	79
6.3.2 Proportion of bodies of water with good ambient water quality	UNEP	II	4 The 1st variable is proportion of bodies of water with good ambient water quality	2017	52
6.4.2 Level of water stress: freshwater withdrawal as a proportion of available freshwater resources	FAO	I	1 Level of water stress: freshwater withdrawal as a proportion of available freshwater resources	2000, 2005, 2010, 2015	269 (2015)
6.5.1 Degree of integrated water resources management implementation (0–100)	UNEP	I	2 The 1st variable is degree of integrated water resources management implementation	2018	182
6.6.1 Change in the extent of water-related ecosystems over time	UNEP, Ramsar	I	16 The 4th variable is nationally derived proportion of water bodies with good quality	2017	28
7.1.1 Proportion of population with access to electricity	World Bank	I	1 Proportion of population with access to electricity, by urban/rural	2000–2017 (annual)	236 (2017)
9.4.1 CO ₂ emission per unit of value added	UNIDO, IEA	I	3 The 3rd variable is CO ₂ emissions per unit of manufacturing value added	2000–2017 (annual)	182 (2017)
11.1.1 Proportion of urban population living in slums, informal settlements or inadequate housing	UN-Habitat	I	1 Proportion of urban population living in slums	2000, 2005, 2010, 2014, 2016	126 (2016)
11.6.2 Annual mean levels of fine particulate matter (e.g. PM _{2.5} and PM ₁₀) in cities (population weighted)	WHO	I	1 Annual mean levels of fine particulate matter in cities, urban population	2016	215
13.1.1 Number of deaths, missing persons and directly affected persons attributed to disasters per 100,000 population	UNDRR	II	10 The 2nd variable is number of deaths and missing persons attributed to disasters per 100,000 population	2005–2018 (annual)	43 (2018)
14.3.1 Average marine acidity (pH) measured at agreed suite of representative sampling stations	IOC-UNESCO	II	1 Average marine acidity (pH) measured at agreed suite of representative sampling stations	2010–2019 (annual)	3 (2019)

Table 1. Cont.

RS-based SDG Indicator	Custodian	Tier	Available Data		
			No. and Name of Data Variables	Year	No. of Countries/Territories/Regions
14.4.1 Proportion of fish stocks within biologically sustainable levels	FAO	I	1 Proportion of fish stocks within biologically sustainable levels (not overexploited)	2000–2017 (varied interval)	1 (global)
14.5.1 Coverage of protected areas in relation to marine areas	UNEP-WCMC, UNEP, IUCN	I	3 The 2nd variable is coverage of protected areas in relation to marine areas (Exclusive Economic Zones)	2018	192
15.1.1 Forest area as a proportion of total land area	FAO	I	3 The 2nd variable is forest area as a proportion of total land area	2000, 2005, 2010, 2015	292 (2015)
15.2.1 Progress towards sustainable forest management	FAO	I	5 The 4th variable is proportion of forest area with a long-term management plan	2000, 2005, 2010	292 (2010)
15.3.1 Proportion of land that is degraded over total land area	UNCCD	I	1 Proportion of land that is degraded over total land area	2015	294
15.4.1 Coverage by protected areas of important sites for mountain biodiversity	UNEP-WCMC, UNEP, IUCN	I	1 Average proportion of Mountain Key Biodiversity Areas covered by protected areas	2000–2019 (annual)	197 (2019)
15.4.2 Mountain Green Cover Index	FAO	I	3 The 1st variable is Mountain Green Cover Index	2017	276
17.6.1 Fixed Internet broadband subscriptions per 100 inhabitants, by speed	ITU	I	2 The 1st variable is fixed Internet broadband subscriptions per 100 inhabitants, by speed	2000–2018 (annual)	179 (2018)

Twelve RS-based indicators that have statistical data according to the Global SDG Indicators Database are not included in the SDR-ID 2019. These include nine Tier I indicators. Recent updates to the Global SDG Indicators Database may partly explain this inconsistency between these two monitoring platforms. However, one indicator (i.e., 11.2.1) that, according to the Global SDG Indicators Database, had no data as of April 2020 is included in the SDR-ID 2019 [97]. Overall, the information in these two monitoring platforms considered in combination (Figure 3; Table 1) is indicative of the current status of EO contributions to SDG progress monitoring at the global level. Clearly, there is more that needs to be done.

The set of criteria used to select indicators for inclusion in the SDR-ID 2019 might also account for some of the inconsistency between the two monitoring platforms. These criteria were (i) global relevance and applicability to a broad range of country settings, (ii) statistical adequacy, (iii) timeliness, (iv) data quality, and (v) coverage [97]. Given these criteria, it is surprising that indicator 15.1.1 (forest area as a proportion of total land area) was not included in the SDR-ID 2019 (Figure 3) [97], because forest cover data are available in Forest Resources Assessment (FRA) reports (www.fao.org/forest-resources-assessment) published by the FAO—the custodian for indicator 15.1.1 (Table 1) [20]. Unfortunately, the SDR-ID 2019 does not provide any explanation.

Here, some important issues regarding SDG indicator 15.1.1 are highlighted. It is important to note that the forest cover data available in the FRA reports are based on statistics consolidated from country reports, which are not backed up by publicly available geospatial data. For the upcoming 2020 FRA report, FAO is “conducting a participatory global remote sensing survey (FRA 2020 RSS) with the scope of improving estimates of forest area change at global and regional scales.” Accordingly, “the FRA secretariat, in collaboration with the Joint Research Center of the European Commission (JRC) and the FAO working group on remote sensing, has developed a worldwide methodology for the FRA 2020 RSS, which is also scalable to national assessments” (<http://www.fao.org/forest-resources-assessment>).

[//www.fao.org/forest-resources-assessment/remote-sensing/fra-2020-remote-sensing-survey/en/](http://www.fao.org/forest-resources-assessment/remote-sensing/fra-2020-remote-sensing-survey/en/)). A switch to a collaborative remote sensing survey approach with the use of a harmonized method for forest cover mapping is necessary so that forest cover change statistics reported in the future will be comparable across countries, landscapes, and forest monitoring studies that employ RS technologies. More importantly, so that such statistics will be backed up by publicly available geospatial data. At present, forest cover change statistics from the FRA reports are neither comparable nor backed up by publicly available geospatial data.

One major challenge to the implementation of the new approach is the harmonization of the definition of forest. The FAO defines a forest in terms of both tree cover and land use; a forest may include bare areas where trees are expected to regenerate, but areas with tree cover in agricultural or urban land use classes are excluded [65,99]. In contrast, RS-based data (e.g., Global Forest Watch) define forest only in terms of tree cover [63,99]. Harmonization of the definition of forest would help clarify important but conflicting records. For instance, a recent global land change study found that global tree cover increased by 2.24 million km² from 1982 to 2016 as a result of a net gain in the extratropics [66], but this finding contradicts FRA reports of a global decline in forest area [99]. This reported increase in global tree cover is supported, however, by another study that reported a net increase of 5.4 million km² of new leaf area from 2000 to 2017, two-thirds of which was attributed to the greening of croplands and forests [67].

Of these two forest definitions, land use plus tree cover and tree cover alone, the latter has greater potential to harmonize methods for global forest cover monitoring with the application of RS technologies. The use of remotely sensed tree cover as the basis for mapping forest cover and monitoring changes is also timely because, as reported by the GEO in a 2017 press release, full satellite coverage of the world's forests has now been achieved, so that all countries have the data necessary for annual forest cover monitoring (<https://www.earthobservations.org/article.php?id=250>). Nevertheless, if the FAO continues to use the land use plus tree cover concept of forest, the view of this reviewer is that the FAO should ensure the use of a harmonized method for identifying and classifying land use from RS data, not only tree cover. It should also make sure that gross forest cover losses and gains are also reported and backed up by publicly available geospatial data (both raw and processed).

Among databases relevant to the 2030 Agenda for Sustainable Development, the Global SDG Indicators Database (<https://unstats.un.org/sdgs/indicators/database/>) is of primary importance. In terms of geospatial data, the data for the EO4SDG initiative are stored in the Global Earth Observation System of Systems (GEOSS) portal (www.geoportal.org). The UN's Open SDG Data Hub also stores available geospatially referenced data for each SDG (<http://unstats-undesa.opendata.arcgis.com>). Other sources of geospatial data include NASA's Open Data Portal (<https://data.nasa.gov>) and the Center for International Earth Science Information Network (CIESIN) (www.ciesin.org). Other initiatives that make SDG-relevant data available include the Global Partnership for Sustainable Development Data (www.data4sdgs.org) and the Open Data Watch (<https://opendatawatch.com>).

5.3. Challenges, Opportunities, and Insights

The production of data for the other RS-based indicators and the subsequent inclusion of more RS-based indicators in the annual updates of the SDR-ID 2019 are among the current challenges to the realization of the EO4SDG initiative. Other challenges relate to the identification and development of relevant sub-indicators or complementary indicators, because some SDG indicators are not specific enough to be properly addressed at present. For example, indicator 15.3.1, the "proportion of land that is degraded over total land area" has been identified as one of the indicators that can be supported by EO data (Figure 3; Table 1). However, land degradation itself is a broad concept, as indicated by target 15.3: "by 2030, combat desertification, restore degraded land and soil, including land affected by desertification, drought, and floods, and strive to achieve a land degradation-neutral world" [2,3].

To address this issue, three sub-indicators for indicator 15.3.1 have been identified: land cover and land cover change, land productivity, and above- and belowground carbon stocks [24,100]. With

respect to land productivity as a sub-indicator of 15.3.1, a recent study [100] (p. 1) argues that “current use of vegetation indices alone to remotely sense degradation of ecosystem services does not provide an adequate productivity indicator”; thus a more robust methodology is needed. Another study has developed an integrated approach to the operationalization of the three proposed sub-indicators for indicator 15.3.1 [95]. In this approach, all three sub-indicators are taken into account by a modeling process that results in an overall indicator of land degradation [95].

RS data can also be used to examine and identify priority areas for sustainable management to realize targets under SDG 6 (Clean Water and Sanitation) [101]. Furthermore, RS data can also be used to provide evidence for some of the currently identified non-RS-based indicators. For instance, RS data can be used to derive relevant landscape-based indicators (e.g., landscape fragmentation and connectivity metrics) as complementary indicators for assessing the effectiveness of financial investments in the conservation and sustainable use of biodiversity and ecosystems (target 15.a), as well as in sustainable forest management, including conservation and reforestation (target 15.b). RS data can also help operationalize social and economic SDG targets. For instance, RS data can be used to advance the study and monitoring of household poverty [102], which is relevant to targets 1.1 and 1.4. An idea for assessing slavery from space, which is relevant to target 8.7, has also been proposed [103].

According to the Global SDG Indicators Database, some indicators have available data in >200 countries or territories, but others have available data in fewer than 50 (Table 1). Moreover, for some indicators, data are available at multiple spatial scales (regions, countries, and territories), whereas for others, data are available only for countries. To ensure consistency, geographical units for data production, collection, and reporting for global monitoring need to be harmonized across all SDG indicators. Likewise, the baseline year for all SDG indicators may also need to be defined and harmonized. Simply harmonizing the baseline year would help not only the groups that are in charge of data production and collection but also researchers interested in SDG monitoring at the global level.

It is clear that the SDG global indicator framework in general and the RS-based indicators in particular need to be improved. Other current challenges, as well as future research directions, related to SDGs, targets, and indicators include addressing the potential pitfalls (ethical, legal, and reputational) in the compilation and use of big data [104] and the analysis of synergies and trade-offs [101,105–108]. Other important issues include the development of other frameworks for assessing the suitability of EO-derived data for SDG indicators [60] and of another aggregation method for the SDG Index [108], as well as the regionalization (sub-national) of SDG progress monitoring [109]. In particular, for the possible improvement of the SDG Index as presented in the SDR-ID 2019 [97] and in its earlier versions (www.sdgindex.org), an aggregation method based on a multidimensional synthesis of indicators and that takes into account the trade-offs and synergies between goals and targets and across the three pillars of sustainable development (social, economic, and environmental) has been proposed [108]. Regionalized or localized SDG progress monitoring is also particularly important because it allows individual countries to assess their own progress in space and time toward sustainable development [109].

RS-based indicator status as presented here (Figure 3; Table 1) is based solely on the Global SDG Indicators Database. This database only consolidates available statistics at the country or territory and regional levels; it does not include information on the actual availability of the geospatial data (both raw and processed) from which the statistical data were supposedly derived. This is important to note because some of the RS-based indicators identified as already having at least preliminary statistical data (Table 1) may not yet have geospatial data. For example, data for indicator 15.1.1 (forest area as a proportion of total land area) recorded in the database are based on FRA reports, but, as mentioned earlier, these recorded statistical data are not backed up by geospatial data. Some information on the availability of geospatial data are available from the UN Open SDG Data Hub, but it would be better if the GEOSS portal provided information related to the EO4SDG initiative. As of this writing, however, no specific page is dedicated to the currently identified RS-based SDG indicators and for tracking the actual status and availability of raw and processed geospatial data for each of these indicators.

Perhaps future updates of the EO4SDG initiative and the GEOSS portal could address this issue, in collaboration with the concerned designated SDG indicator custodians.

A limitation of this review is that it is only an overview of the conceptualization of sustainability leading to the formulation of the SDGs and of the current status, challenges, and opportunities in SDG monitoring with RS. Some important issues need to be covered at greater depth, such as (i) the applications of RS, including data availability, across ecosystems but with particular focus on the SDGs, (ii) how the number of SDG indicators might be different from one ecosystem to another, (iii) challenges and opportunities of RS data in terms spectral and spatial resolutions as applied across ecosystems, (iv) how the SDG indicators were decided (e.g., how much is based on concerns in terms of the economic, social, and environmental pillars of sustainability and how much is based on logistics, e.g., data availability), and (v) the specific issues about the SDG global indicator framework, e.g., inappropriateness of some of the (initial) indicators.

6. Conclusions

Although the concept of sustainability, the idea that the current generation has responsibility for future generations, originated at least as far back as the 17th century, according to the UN-GSDR 2019, the world is not on track for achieving most of the targets that comprise the SDGs by the target date of 2030. Meanwhile, through the EO4SDG initiative of the GEO, the full potential of RS for SDG monitoring is now being explored at a global scale. As of April 2020, 21 (70%) of the RS-based SDG indicators already have at least some preliminary statistical data according to the Global SDG Indicators Database, and 10 (33%) of the RS-based SDG indicators are included in the SDR-ID 2019. These statistics, however, do not necessarily reflect the actual status and availability of raw and processed geospatial data for the RS-based indicators, which remains an important issue. Nevertheless, various initiatives have also been started to address the need for open access data. RS data can also help in the development of potentially relevant complementary indicators or sub-indicators, which will help address one of the current challenges in SDG monitoring, which is how to operationalize the SDG indicators.

Author Contributions: R.C.E. conceptualized this review. He performed the review, prepared all the tables and figures, and wrote the paper. The author has read and agreed to the published version of the manuscript.

Funding: This research was supported by the Japan Society for the Promotion of Science (JSPS), through Grant-in-Aid for Young Scientists (B): 20K13262 (PI: Ronald C. Estoque).

Acknowledgments: This work was also supported by the Climate Change Adaptation Program of the National Institute for Environmental Studies, Japan. The author also acknowledges the four anonymous reviewers whose comments and suggestions helped improve this manuscript.

Conflicts of Interest: The author declares no conflict of interest.

Appendix A

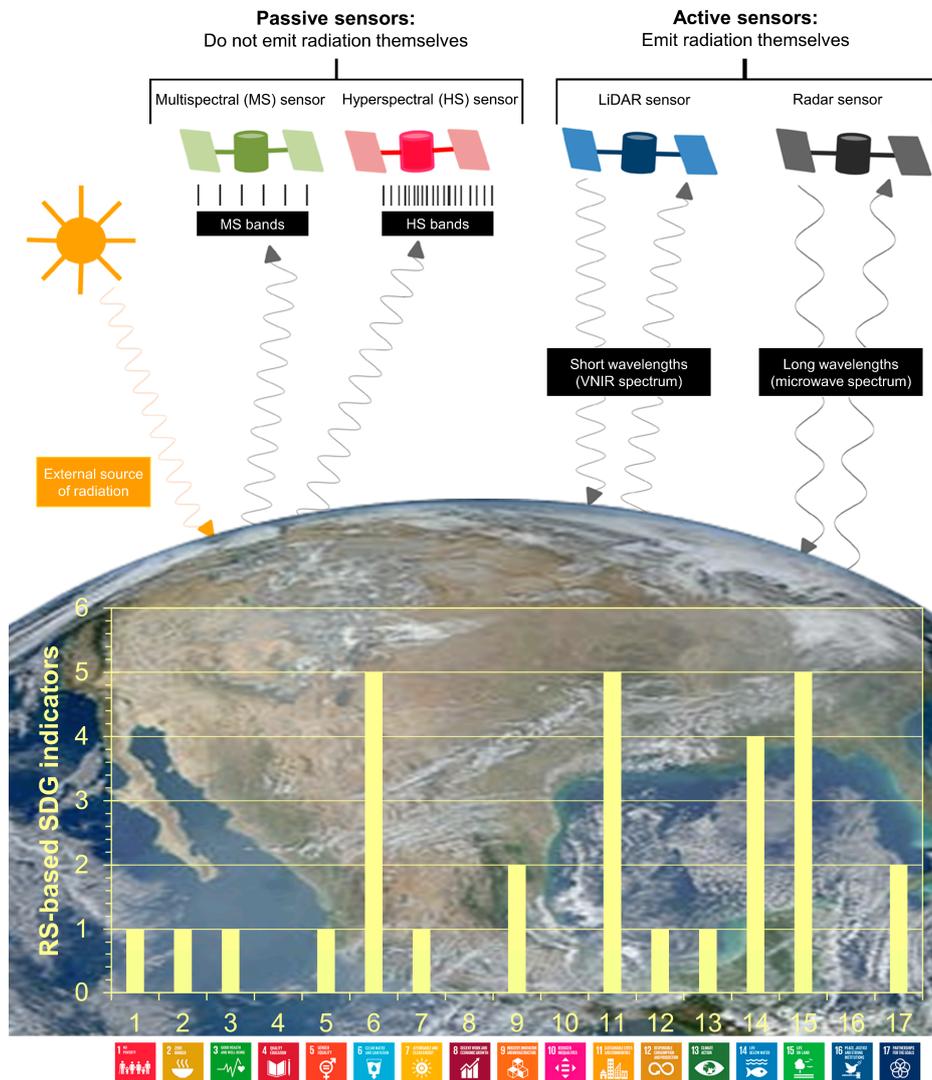


Figure A1. Contributions of RS to SDG monitoring. The diagrams of passive and active remote sensors are from [110]. Passive sensors (e.g., multispectral and hyperspectral sensors) rely on an external source of energy (the sun) and record the radiation reflected by Earth’s surface to produce an image, whereas active sensors (e.g., LiDAR and Radar) emit energy in the microwave part of the electromagnetic spectrum and measure the amount of energy reflected back at them [110]. The column graph shows the number of indicators for each of the 17 SDGs to which Earth Observation data can contribute, directly or indirectly [25].

Table A1. Widely used multispectral satellite RS data.

Satellite	Sensor and Number of Bands	Spatial Resolution	Revisit Interval	Reference
Landsat 4/5 TM	MS 6; T 1	MS & T: 30 m	16 days	[111]
Landsat 7 ET+/8 OLI/TIRS	MS 6/8; T 1/2; Pan 1	MS & T: 30 m Pan: 15 m	16 days	[111]
SPOT 1/2/3 (2 HRVs)	MS 3; Pan 1	MS: 20 m Pan: 10 m	1 to 3 days	[112]
SPOT 4 (2 HRVIRs)	MS 4; Pan 1	MS: 20 m Pan: 10 m	2 to 3 days	[112]
SPOT 5 (2 HRGs)	MS 4; Pan 2	VNIR: 10 m; SWIR: 20 m Pan: 5 m (2.5 m)	2 to 3 days	[112]
SPOT 6/7 (2 NAOMI)	MS 4; Pan 1	MS: 8 m Pan: 2 m	Daily	[113]
NOAA AVHRR	MS & T 4–5	1.1 km	Daily (Vis), 2×/day (IR)	[114]
OrbView 2 (SeaWiFS)	MS 8	1 km	Daily	[113]
IKONOS 2	MS 4; Pan 1	MS: 3.20 m Pan: 0.82 m	1 to 3 days	[113]
Terra ASTER	MS up to 10; T 5	VNIR: 15 m; SWIR: 30 m, T: 90 m	All bands: at least 1×/16 days, VNIR: 5 days	[115]
MODIS Terra/Aqua	MS & T 36	Bands 1–2: 250 m, Bands 3–7: 500 m, Bands 8–36: 1 km	1 to 2 days	[116]
Envisat MERIS	MS 15	Ocean: 1040 m × 1200 m; Land: 260 m × 300 m	3 days	[117]
QuickBird	MS 4; Pan 1	MS: 2.40 m Pan: 0.60 m	1.5 to 2.8 days	[117]
GeoEye	MS 4; Pan 1	MS: 1.64 m Pan: 0.41 m	≤ 3 days	[113]
RapidEye	MS 5	MS: ~6.5 m	1 to 5.5 days	[117]
WorldView 2	MS 8; Pan 1	MS: 1.80 m, Pan: 0.46 m	1.1 days	[113]
Sentinel 2A/2B	MS 13	MS: 10 m, 20 m, 60 m	A or B: 10 days A & B: 5 days	[118]

Abbreviations: MS, multispectral band; T, thermal band; Pan, panchromatic band; SWIR, short-wave infrared; VNIR, visible and near infrared; Vis, visible; IR, infrared.

Table A2. Widely used radar satellite RS data.

Satellite	Sensor	Spatial Resolution	Revisit Interval	Reference
ERS 1/2	C-band SAR	30 m to 50 km	35 days	[113]
JERS 1	L-band SAR	18 m	44 days	[113]
RADARSAT 1/2	C-band SAR	10–100 m/ 3–100 m	24 days	[117]
Envisat ASAR	C-band SAR	28–980 m	35 days	[117]
ALOS PALSAR	L-band SAR	7–100 m	46 days	[119]
TerraSAR-X	X-band SAR	1–16 m	11 days	[117]
TanDEM-X	X-band SAR	12 m	11 days	[117]
ALOS-2	L-band SAR	3–100 m	14 days	[119]
Sentinel 1/2 SAR	C-band SAR	5–100 m	1/2: 6 days; 1 or 2: 12 days	[118]

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